NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE EFFECT OF DEAD RISE UPON THE LOW-ANGLE TYPE

OF PORPOISING

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NACA

WASHINGTON

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SUMMARY

Data pertaining to the forces and moments developed by V-bottom planing surfaces of different angles of dead rise were used to compute the effect of the dead rise of the forebody upon the lower trim limit of stability of a seaplane, the trim limit of stability being defined as the trim below which the seaplane is unstable. The results of the calculations were checked experimentally, with very good agreement, by use of a simplified model composed of a planing forebody and a tail plane having a controllable elevator. The calculations included three angles of dead rise, each at one speed and one load. The tests included a wide range of speeds and loads likely to occur during the take-off or landing. The results indicated in every case that an increase in dead rise within the range investigated (10° to 30°) caused an important increase in the lower trim limit of stability.

The present investigation also included tests of a model having a transverse section incorporating chine flare and an abrupt increase in dead rise at a point one-third of the beam outboard of the keel. This complex section proved to have very interesting stability characteristics at planing speeds near the hump where the lower trim limit was not greatly affected by load. These characteristics are in marked contrast to those of a simple V-bottom and indicate that departures from the simple shape of transverse section may produce results that cannot safely be predicted by assuming an equivalent V-bottom.

A survey of the important variables involved in the low-angle type of porpoising is included to show the relation of the results of the present investigation to the general problem.

INTRODUCTION

A great deal of experimental work on porpoising of models has been done at the NACA tank and elsewhere. Most of the work has been concerned with specific designs for military use and the information obtained has been restricted in circulation. Considerable information has been accumulated to show the effects of modifications that may be incorporated without great difficulty in an existing design. Among the variables that have been investigated are depth and plan form of the step, the moment of inertia, and the longitudinal position of the center of gravity. The results of the investigations in general have indicated that the effects of the above variables are not great within the ranges that were included in modifying specific designs. The restriction of most of the work to consideration of specific designs has limited the investigations and it appears that the effect of dead rise has not been included.

Reference 1 presents an adaptation of the conventional methods of stability analysis to the phenomenon of porpoising; simplified equations for the lift and moment of a flat planing surface and for two surfaces in tandem are used for calculating the stability derivatives. Reference 2 describes methods of computing the stability derivatives from the results of tank tests of a model. Reference 3 describes a method of investigating the phenomenon of low-angle porpoising by use of a simple apparatus including a single planing surface with tail plane.

The present report presents results showing the effect of dead rise as computed by methods similar to those described in references 1 and 2. The results of tests using the method and apparatus described in reference 3 are also presented and compared with the results of the computations. The computations were made for three angles of dead rise at one load and one speed. The tests include a wide range of loads and speeds representing the range between the hump speed and the get-away speed of a flying boat.

CALCULATION OF THE EFFECT OF DEAD RISE ON STABILITY

Theory.- A calculation of the effect of dead rise on stability was made on the basis of the analysis developed

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by Perring and Glauert (reference 1) in an adaptation of the methods customarily employed in the analysis of the longitudinal stability of an airplane in flight. Perring and Glauert demonstrated that valid results may be obtained if the fore-and-aft oscillations are neglected and the seaplane is considered to be a system having two degrees of freedom: namely, freedom in rise and freedom in trim about the center of gravity. The derivatives of order higher than 1 are neglected and the equations of motion referred to unit mass and unit moment of inertia are

$$\lambda^2 z = Z_w \lambda z + Z_z z + Z_q \lambda \theta + Z_\theta \theta$$

$$\lambda^2 \theta = M_w \lambda z + M_z z + M_q \lambda \theta + M_\theta \theta$$

z distance along OZ axis, positive downward

θ angle of trim about lateral axis, positive when bow is elevated

w vertical velocity, $\frac{dz}{dt}$

q angular velocity, $\frac{d\theta}{dt}$

Z force (per unit mass) along OZ axis

M moment (per unit moment of inertia about center of gravity)

λ used for operator $\frac{d}{dt}$

$Z_w = \frac{\partial Z}{\partial w}$

$M_z = \frac{\partial M}{\partial z}$

Etc. for Z_z, Z_q, Z_θ, M_w, M_q, and M_θ.

The axes are taken as right hand and are fixed relative to the water surface, moving with the seaplane and with the origin at the center of gravity of the seaplane when there is no porpoising oscillation.

From the two equations of motion the stability equation is derived in its usual form

$$A\lambda^4 + B\lambda^3 + C\lambda^2 + D\lambda + E = 0$$

where

$$A = 1$$

$$B = -(Z_w + M_q)$$

$$C = -(Z_z + M_\theta - Z_w M_q + Z_q M_w)$$

$$D = Z_z M_q - Z_q M_z + Z_w M_\theta - Z_\theta M_w$$

$$E = Z_z M_\theta - Z_\theta M_z$$

The system is stable if A, B, C, D, E, and R are positive, R being Routh's discriminant and equal to

$$BCD - AD^2 - B^2 E$$

<u>Evaluation of the derivatives</u>.- Reference 4 was used as the source of data in the evaluation of the hydrodynamic components of the derivatives for 10°, 20°, and 30° dead rise. The computations were carried out as described in reference 2 except that the effect of Froude's number $V/\sqrt{gb}$ was neglected. Neglecting this effect appeared justified because plots of the planing coefficient $\dfrac{\Delta}{\frac{1}{2}\rho V^2 b^2}$ against the draft and of the resistance coefficient $\dfrac{R}{\frac{1}{2}\rho V^2 b^2}$ against the draft resulted in curves that appeared practically independent of the speed over the range applicable to the calculations. The symbols in these expressions are defined as follows:

Δ load on planing surface

R resistance

ρ density of water

V speed

b beam

Drafts were computed from wetted lengths in preference to the use of values for the draft tabulated in reference 4. Using values of the wetted length appeared advisable because surges in a towing basin may cause erratic readings and may also introduce a systematic error in the usual method of measuring draft with reference to some point on the towing carriage.

From the plots mentioned and from plots of the location of the center of pressure as a function of draft and trim, together with cross plots derived from them, the values of the derivatives were obtained in the usual way from the slopes of the curves. The calculations were carried out for the one combination of speed, load, moment of inertia, and location of the center of gravity noted in table I. The calculations were for the system with tail but without wing and also for the system with both wing and tail. The effect of the wing was investigated in order to see if sufficient accuracy is to be expected in using a simplified experimental set-up in which the wing is absent.

Results of the calculations.- The values of the stability derivatives, the terms in the discriminant equation, and Routh's discriminant are listed in table I. The values are for unit mass and unit moment of inertia and are dimensional, involving forces and moments acting on a planing surface with a beam of 1.33 feet at a speed of 40 feet per second. Dimensional values were used to facilitate comparison directly with results obtained during the experimental work with a model having the same beam.

The values of Routh's discriminant for each angle of dead rise are plotted against trim in figure 1. The plots include results for the planing surface with wing and tail and also for the planing surface with the tail alone. The wing appears to have very little effect upon the trim at which Routh's discriminant passes through zero. An examination of table I shows that A, B, C, D, and E are all positive when Routh's discriminant is near zero, and that it is the discriminant in each of these cases that indicates whether the system is stable or unstable.

The results indicate that an increase in angle of dead rise from 10° to 30° causes an increase of about $4\frac{1}{2}^\circ$ in the trim at which R passes through zero (fig. 1).

EXPERIMENTAL INVESTIGATION

Models

Figure 2 shows a sketch of the apparatus and shows the shape of the transverse section of the bottom of each of the models designated A, B, C, and D. Model B is the same as that used in the tests described in reference 3. The keel of each of the four models is straight for a distance of 36 inches forward of the trailing edge, the beam of each is 16 inches, and the over-all length is 48 inches. Each model was fitted with a tail plane of NACA 0015 section of rectangular plan form and with a span of 41 inches. The chord of the stabilizer was $6\frac{1}{2}$ inches and that of the elevator $5\frac{3}{4}$ inches. The moment arm of the tail plane was approximately 48 inches.

Test Procedure

The test procedure was practically the same as that described in reference 3. The model was towed at the low-water level in the NACA tank. Runs were made at constant speed and with fixed loads on the water, while the trim of the model was adjusted by means of the elevator. In the present tests the method of establishing the critical trim was practically the same as that described in reference 3.

As defined in reference 3, the critical trim is that value of the trim separating the stable range from the unstable range of trim, the upper range being the stable one. For each test point, the bow of the model was raised about 2° and released. If regular oscillations followed, the trim was assumed to be below the critical value. If the oscillations of the model decayed to zero in a few cycles, the trim was considered to be above the critical value. Points definitely above and below the critical value, separated by as small a range as appeared practical, were established and the critical trim was assumed to be the mean between the two values. Check tests of the critical trim by independent observers usually produced results differing by not more than $\frac{1}{2}^\circ$.

Results

Results of the tests of the four planing models are presented in figure 3 showing the variation of critical trim with speed for loads of 40, 60, 80, and 100 pounds. In coefficient form these loads are, respectively, 0.26, 0.39, 0.52, and 0.65, the load coefficient being defined by the formula

$$C_\Delta = \Delta/wb^3$$

where w, the specific weight of water in the tank, is 63.4 pounds per cubic foot and b, the beam of the model, is 1.33 feet. The mass of the model including all counterweights was 4.8 slugs, corresponding to a gross load coefficient of 0.93, and the radius of gyration was 1.23 feet for the results shown in figures 3 and 4. The present tests did not include extensive variations of gross weight, radius of gyration, or location of the center of gravity. Reference 3 describes the effect of these variables for an angle of dead rise of $22\frac{1}{2}°$ and shows that the radius of gyration is the only one of the three variables that appears to be very important in determining the critical trim. The conclusion in reference 3, that decreasing the radius of gyration caused an increase in the critical trim, was checked qualitatively during the present tests by obtaining the critical trim in the usual manner and then increasing by about 100 percent the mass moving vertically without changing the speed or load on the water. Each of the three models having a simple V-bottom invariably showed an increase in the critical trim.

The anomalous results obtained with planing model D at speeds from 24 to 34 feet per second were investigated with considerable interest. Intersection of some of the curves shown in figure 3(d) was unmistakably established. For instance, at 30 feet per second the trim of the model was adjusted to be slightly but definitely above the critical value for a load of 100 pounds. With the model running stably, the load was reduced to 60 pounds and porpoising followed.

DISCUSSION

<u>Comparison of calculated with experimental results</u>.- In figure 5(c) the dashed curve shows the variation of critical trim with angle of dead rise as calculated. The calculated curve is in very good agreement with the experimental results. The agreement appears sufficiently

good to justify further use of the data in table I for calculations to show the effect of other variables, such as the radius of gyration and the location of the center of gravity, in combination with the effect of dead rise.

<u>Experimental results</u>.- The faired curves of figure 3 were used to obtain the comparisons in figures 4 and 5 showing the effect of dead rise for the three simple V-bottoms. The increase of critical trim with increase of dead rise is definite and rather large for all loads and speeds included. For example, figure 5(b) shows that with a load of 60 pounds at 30 feet per second an increase in angle of dead rise from 15° to 30° causes an increase in critical trim from about 5.2° to 9.4°. The magnitude of the effect of dead rise is interesting in view of the many parameters that have no important effect upon the lower limit of porpoising of a seaplane.

Heretofore the selection of the angle of dead rise has been influenced mainly by consideration of its effect upon resistance, spray, and impact pressures. To these considerations must now be added the effect of dead rise upon stability. A consideration of the effect of dead rise upon the porpoising characteristics of a complete seaplane should, of course, take into account the effect upon the upper limit and upon skipping. No information appears to be available at present regarding the effect of dead rise upon the upper limit of stability.

K. S. M. Davidson and F. W. S. Locke of Stevens Institute of Technology have used plots (results of unpublished tests made in the experimental towing tank at Stevens Institute) of the lower trim limit of stability against $\frac{\Delta}{\frac{1}{2}\rho V^2 b^2}$, in which the data obtained at Stevens Institute for several different loads fell rather close to a single curve. Similar plots of the data obtained in the present tests of planing surfaces are shown in figure 6. The data for models A and B show relatively small variations with load. For models C and D the variations are somewhat greater.

A partial explanation of the result that the effect of load appears to be small may be obtained by a consideration of the methods used in the present report for calculating the effect of dead rise on stability. The derivatives were calculated by using the concept of a planing coefficient that neglects the effect of Froude's number. This procedure of neglecting Froude's law of comparison is frequently employed in the analysis of planing phenomena and implies that a given configuration of trim, draft, beam, and dead rise results in a single value for $\frac{\Delta}{\frac{1}{2}\rho V^2 b^3}$. Likewise, there is a single value of $\frac{R}{\frac{1}{2}\rho V^2 b^2}$ and also of the position of the center of pressure. Thus, if the ratio Δ/V^2 is held constant, variations in Δ and V result in variations of R but do not vary either the ratio R/V^2 or the position of the center of pressure. Accordingly, for a constant value of Δ/V^2, a variation in the load affects all the derivatives by some constant factor and does not affect the sign of any of the terms in the discriminant equation or the sign of Routh's discriminant. If the assumptions were correct, the plots of figure 6 would be independent of load for the three V-bottom models. The comparatively small effects of the load shown do indicate that the assumptions were good approximations.

SURVEY OF THE GENERAL PROBLEM

As a convenience in showing the relation of the results of the present investigation to the general problem of porpoising, an outline of some of the more important variables is given:

I. Factors variable during a take-off or landing

A. Speed

B. Hydrodynamic load (gross weight minus aerodynamic lift)

C. Trim

II. Variables in the configuration of the airplane

A. Aerodynamic

1. Lift, affected mainly by

a. Wing area

b. Slope of lift curve and stall angle

c. Angle of wing setting

2. Damping in angular velocity, affected mainly by

a. Tail area

b. Tail length

3. Damping in vertical velocity, affected mainly by slope of lift curve

B. Hydrodynamic

1. Dead rise and shape of transverse section

2. Plan form of trailing edge of forebody

3. Longitudinal curvature of forebody

C. Inertial

1. Total mass

2. Moment of inertia

3. Location of center of gravity

This outline relates only to the low-angle type of porpoising that does not involve the afterbody. The length of the forebody is assumed to be sufficient to prevent the bow from entering the water. The effects of speed, load, and trim are well known, at least in a qualitative way. An increase in speed, a decrease in load, or an increase in trim all tend to decrease the probability of porpoising.

An increase in aerodynamic damping in pitch may reduce the probability of porpoising, although an increase in this damping beyond a certain point may have no practical value in reducing porpoising and may, in fact, be undesirable. Perring and Glauert (reference 1) showed that if no aerodynamic damping were present, porpoising definitely would be more probable. The result of Perring and Glauert's analysis has been amply verified experimentally. Unpublished results of tests made by Davidson and Locke of Stevens Institute of Technology showed the effect of varying the tail damping from zero to twice the designed value on a model of a large flying boat. They showed very little effect at speeds near the hump. At speeds near get-away an increase in damping from zero to the designed value reduced the lower limit from 4.5° to 1.6°. Further increase in the damping to twice the designed value reduced the lower limit by an additional amount of only about 0.2°. These results are in agreement with the results described in reference 3, wherein it was concluded that when the tail area was doubled there was no very important effect upon the lower limit. The tests described in reference 3 included a further consideration of tail area in an investigation of its effect upon the amplitude of porpoising that occurs when the trim falls below the lower limit. The amplitude of the porpoising was found to be increased somewhat when the tail area was increased. Thus, it appears that an increase in tail area may not necessarily be of any advantage in reducing porpoising.

The effect of wing damping was considered in reference 3. The effect is confined mainly to the derivative Z_w and was found to be not very important. In the tests at Stevens Institute referred to, Davidson and Locke found no effect from increasing the aerodynamic component of Z_w from the designed value to about twice that value.

The effects of many variations in the plan form of the trailing edge (step) have been investigated at NACA tank no. 1. The effects upon the lower limit have been generally very small. Brief tests of one planing surface and of one complete model of a flying boat having an elongated form in which the chines were faired into a pointed step showed some increase in the lower trim limit of stability.

No information appears to be available regarding the effect of longitudinal curvature of the forebody upon porpoising. An indication of the effect of this variable should be predictable from calculations of the type presented in the present report. Data for calculating the values of the derivatives may be obtained from reference 5.

Investigations of the effects of mass, moment of inertia, and center of gravity have been comparatively numerous. Small changes in mass and moment of inertia (on the order of ±25 percent) appeared to have negligible effects. Reference 3 shows that changes in the radius of gyration ($\sqrt{I/M}$), on the order of a 50-percent decrease or a 100-percent increase, may have very important effects upon both the lower limit and the amplitude of porpoising. The larger radius of gyration appeared desirable and possibly accounted, at least in part, for the fact that float seaplanes generally exhibit less severe porpoising than flying boats.

Many efforts have been made to improve the porpoising characteristics of a seaplane by moving the center of gravity (for example, see references 6 and 7). The principal effect in the case of a complete airplane appeared to be that resulting from the change obtained in the range of trim available. Reference 3 indicated that there was only a relatively small and unimportant effect upon the lower limit of stability.

When the results of the information outlined above are summarized, only two variables in configuration appear known to be of much importance in determining the lower trim limit of stability of a seaplane: namely, the radius of gyration and the shape of the transverse section.

The conflicting requirements of low resistance during planing and of an easy entry on impact lead to compromises by the designer of a seaplane in selecting the dead rise. Numerous complex shapes including fluted bottoms and bottoms similar in shape to that of planing model D have appeared to many designers to offer some advantages over a simple V-bottom with chine flare. The results obtained in the tests of model D indicate that the lower limit of stability may not be accurately predicted by assuming it to be equivalent to some average value of the dead rise. The anomalous behavior of model D over a narrow speed range above the hump also indicates that a complex form may offer some advantages as a compromise by reducing the probability of low-angle porpoising for a heavy load at speeds in the lower end of the planing range, where low-angle porpoising frequently occurs in conventional designs. At speeds below this range the afterbody ordinarily becomes involved, and in many cases at higher speeds the probability of the low-angle type of porpoising is remote.

CONCLUSIONS

The effect of dead rise on the stability characteristics of a complete seaplane should take into account the high-angle type of porpoising and skipping. No information appears to be available at present regarding the effect of dead rise upon types of porpoising that involve the afterbody.

The following conclusions obtained in an investigation of the simplified system composed of a tail plane and planing surface are believed to apply to a complete seaplane when planing on the forebody:

1. Increase of the angle of dead rise within the range of 10° to 30° causes an important increase in the lower limit of stability.

2. Transverse sections of the forebody having complex shapes (for example, a fluted shape) may produce anomalous results that may not be accurately predicted by assuming an equivalent V-bottom.

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TABLE I

VALUES OF THE STABILITY DERIVATIVES AND THE COEFFICIENTS IN THE STABILITY EQUATION

FOR PLANING SURFACES HAVING THREE DIFFERENT ANGLES OF DEAD RISE

[Speed, 40 fps (C_V = 6.11); load, 60 lb (C_Δ = 0.40); beam, 1.33 ft; mass, 5.05 slugs (C_{Δ_0} = 1.08); moment of inertia, 5.2 slug-ft^2; center of gravity, 1.25 beam above keel, 0.32 beam forward T.E.; tail area, 3.47 sq ft; aspect ratio of tail plane, 3.4; tail arm, 3.93 ft; the value of A is unity throughout]

Trim (deg)	Components of derivatives	Stability derivatives								Aerodynamic structure	Coefficients in stability equation				Routh's discriminant, R
		Z_z	Z_w	Z_θ	Z_q	M_z	M_w	M_θ	M_q		B	C	D	E	
Dead rise, 10°															
2	Hydrodynamic	-264	-4.60	-302	3.43	376	2.950	-117.9	3.36	Without wing	3.5	387	-204	149,720	-275.0×10[4]
	Aerodynamic[a]	0	-1.15	-46	0	0	-.479	-19.1	-2.26	With wing	4.7	386	68	167,016	-355.6
	Total	-264	-5.75	-348	3.43	376	2.471	-137.0	1.10						
4	Hydrodynamic	-314	-3.00	-243	-.60	66	.506	-20.2	.004	Without wing	5.3	360	874	28,378	10.0
	Total	-314	-4.15	-289	-.60	66	.027	-39.3	-2.26	With wing	6.4	363	921	31,414	-2.7
6	Hydrodynamic	-326	-2.77	-227	-1.00	7	.470	-19.0	-.17	Without wing	5.2	374	903	14,009	52.3
	Total	-326	-3.92	-273	-1.00	7	-.009	-38.1	-2.43	With wing	6.4	374	946	14,331	76.6
Dead rise, 20°															
4	Hydrodynamic	-169	-4.12	-231	.92	70	.466	-18.6	.34	Without wing	6.1	215	418	22,511	-44.6
	Total	-169	-5.27	-277	.92	70	-.013	-37.7	-1.92	With wing	7.2	217	469	25,761	-82.6
5	Hydrodynamic	-183	-2.30	-157	-.41	49	.287	-11.5	.04	Without wing	4.5	218	466	13,293	-2.6
	Total	-183	-3.45	-203	-.41	49	-.192	-30.6	-2.22	With wing	5.7	221	492	15,547	-12.7
6	Hydrodynamic	-199	-1.69	-134	-.81	18	-.653	-26.2	-.21	Without wing	4.2	195	348	1,082	14.0
	Total	-199	-2.84	-180	-.81	18	-1.132	7.1	-2.47	With wing	5.3	198	289	1,810	16.9
8	Hydrodynamic	-213	-1.40	-114	-.75	-7	-.278	11.3	-.19	Without wing	3.9	223	441	863	17.1
	Total	-213	-2.55	-160	-.75	-7	-.757	-7.8	-2.45	With wing	5.0	227	425	541	28.8
Dead rise, 30°															
5	Hydrodynamic	-118	-3.54	-184	1.57	87	-.779	31.2	-.32	Without wing	6.1	117	-106	14,500	-48.6
	Total	-118	-4.69	-230	1.57	72	-1.258	12.1	-2.58	With wing	7.3	120	-180	18,582	-116.7
6	Hydrodynamic	-127	-2.60	-147	.42	70	-.292	11.7	-.03	Without wing	4.9	141	167	11,230	-19.0
	Total	-127	-3.75	-193	.42	70	-.771	-7.4	-2.29	With wing	6.0	143	140	14,450	-42.0
8	Hydrodynamic	-143	-1.84	-113	-.33	36	.052	-2.1	.01	Without wing	4.1	168	324	7,100	-.1
	Total	-143	-2.99	-159	-.33	36	-.427	-21.2	-2.25	With wing	5.2	171	329	8,756	-5.2

[a]Aerodynamic components of derivatives are the same for all angles of trim and dead rise.

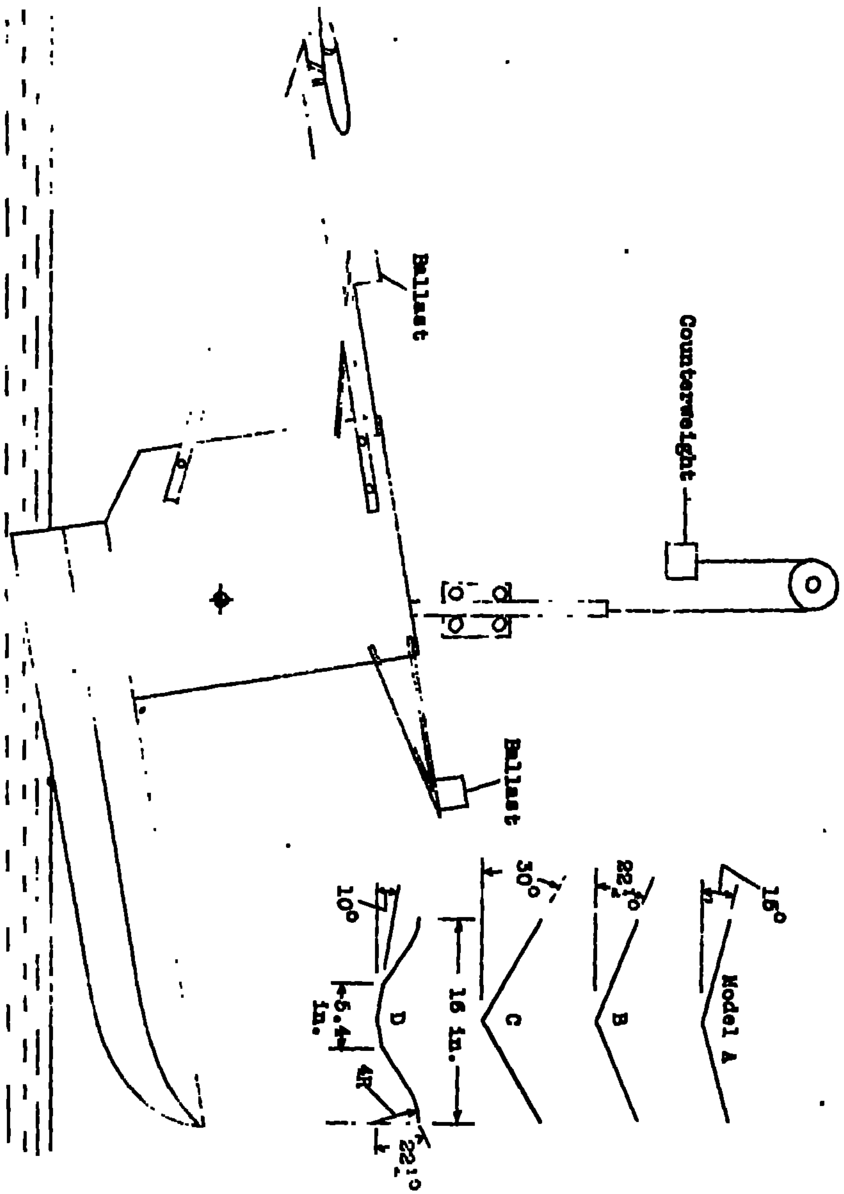

Figure 2.- Sketch of model and arrangement for towing.

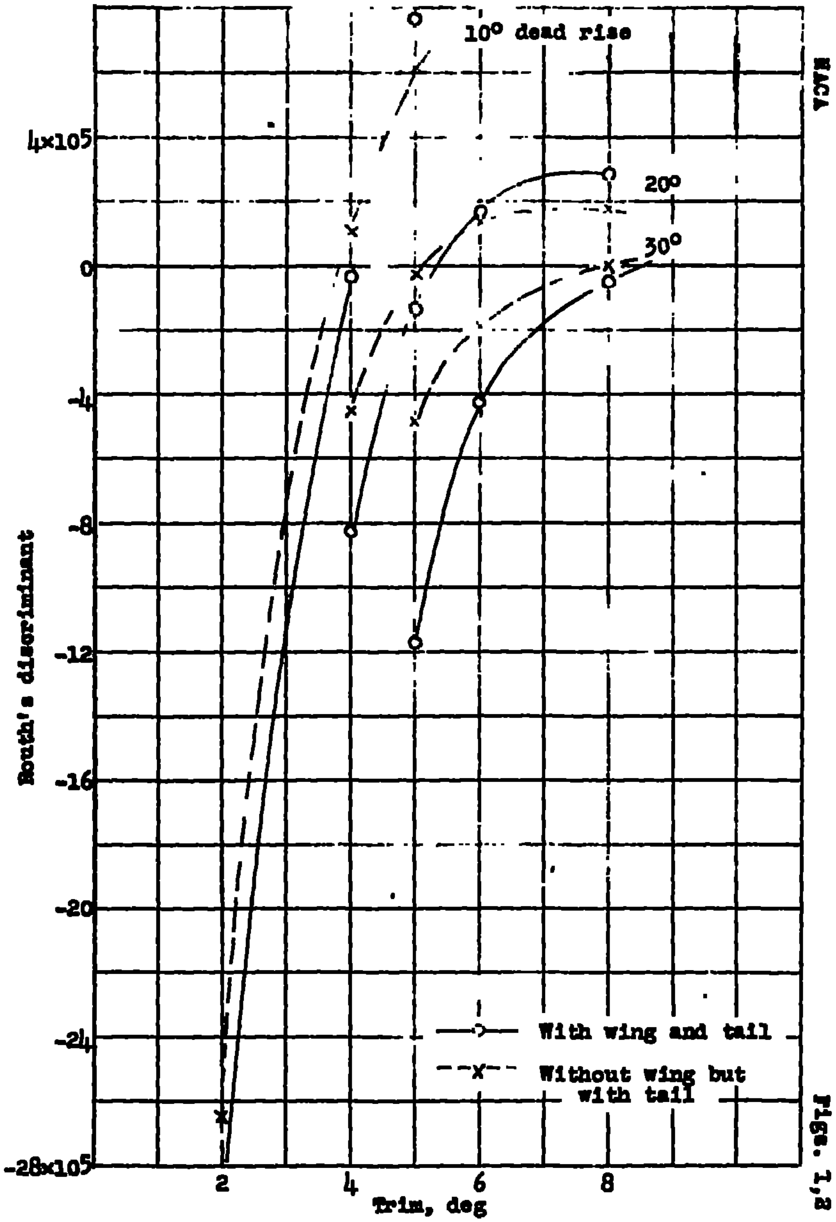

Figure 1.- Variation of Routh's discriminant with trim for three different angles of dead rise.

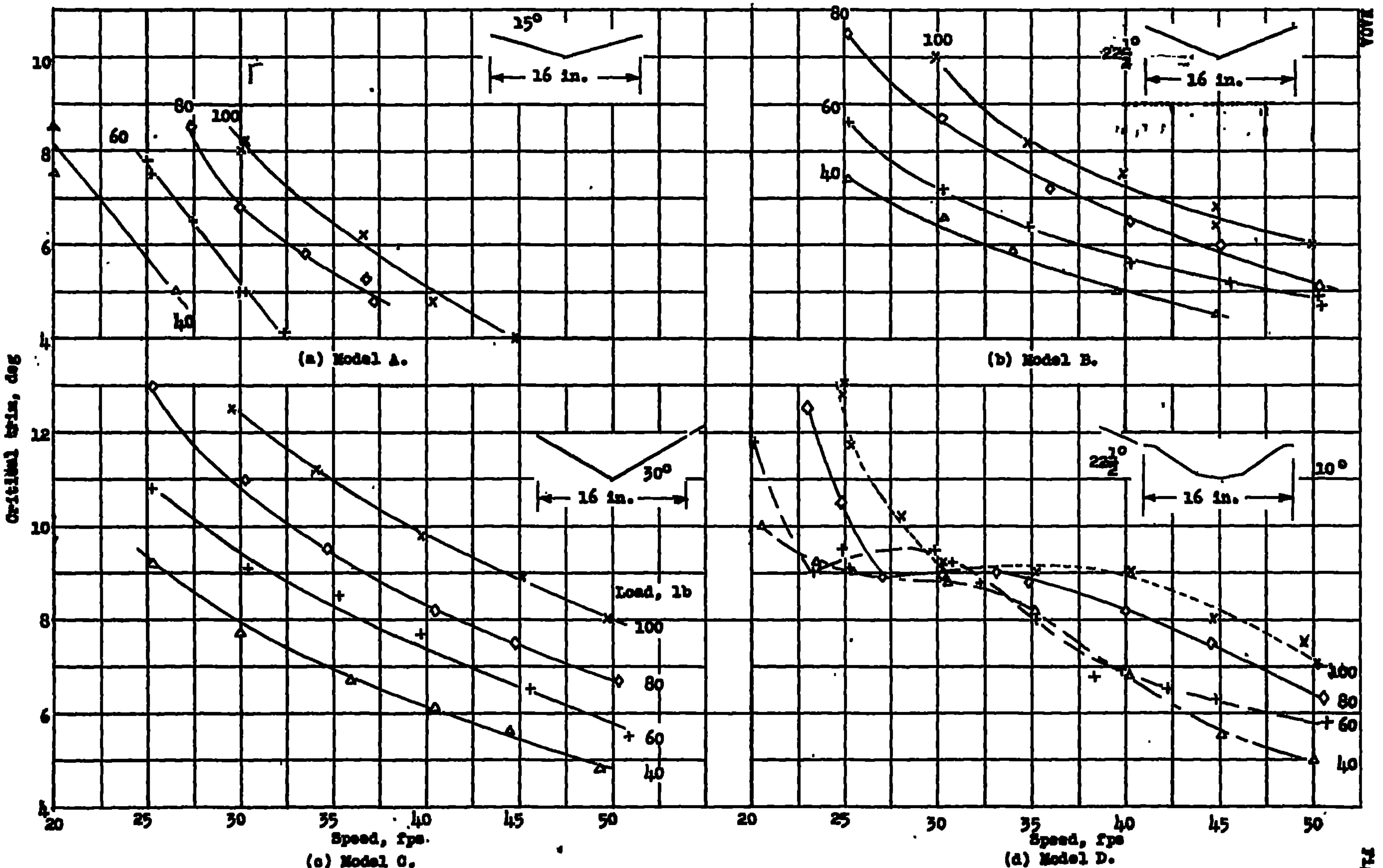

Figure 3.- Variation of critical trim with speed for four planing surfaces of different dead rise, each with four different loads.

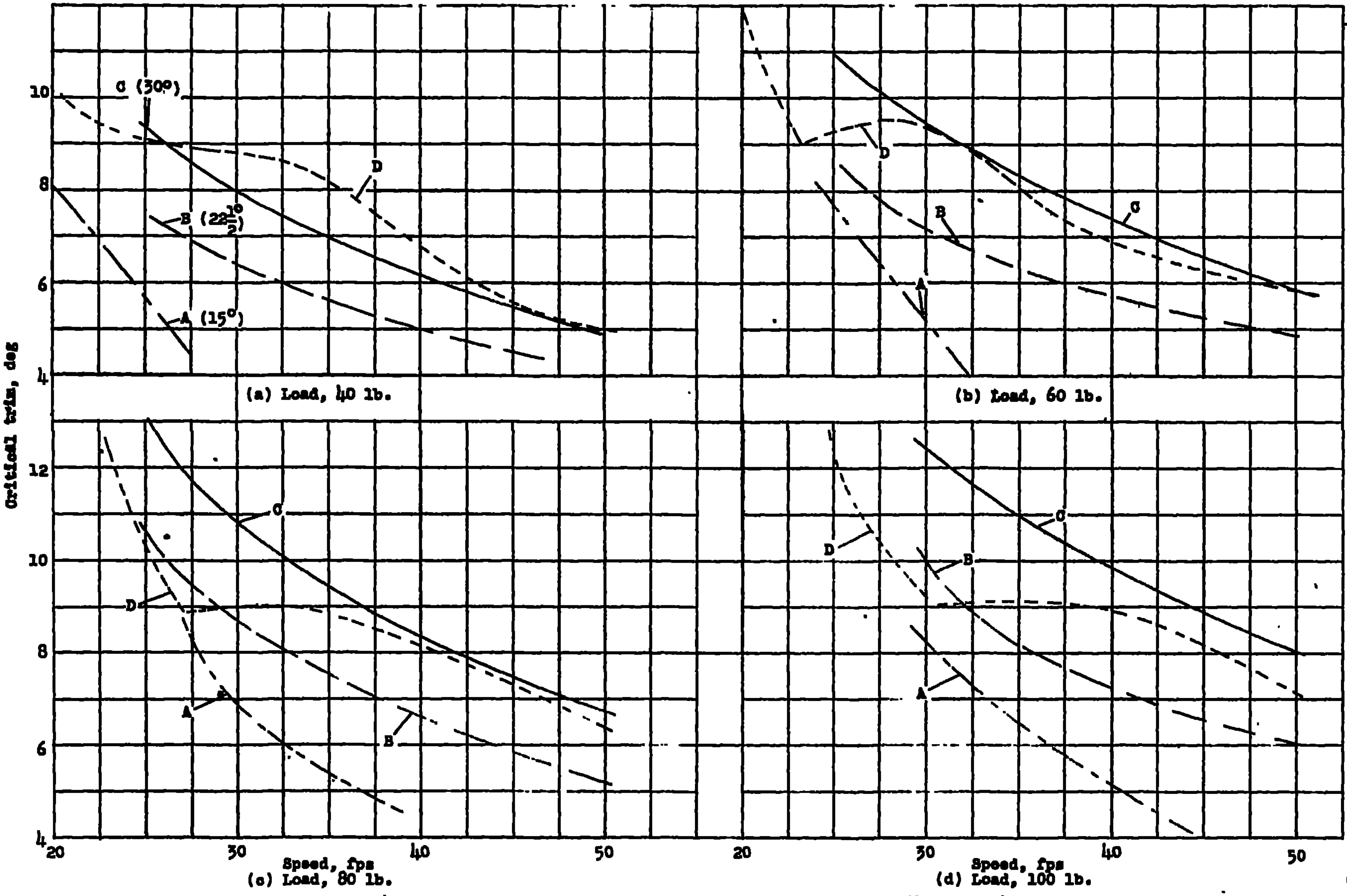

Figure 4.- Faired curves of figure 3 arranged with dead rise as the parameter.

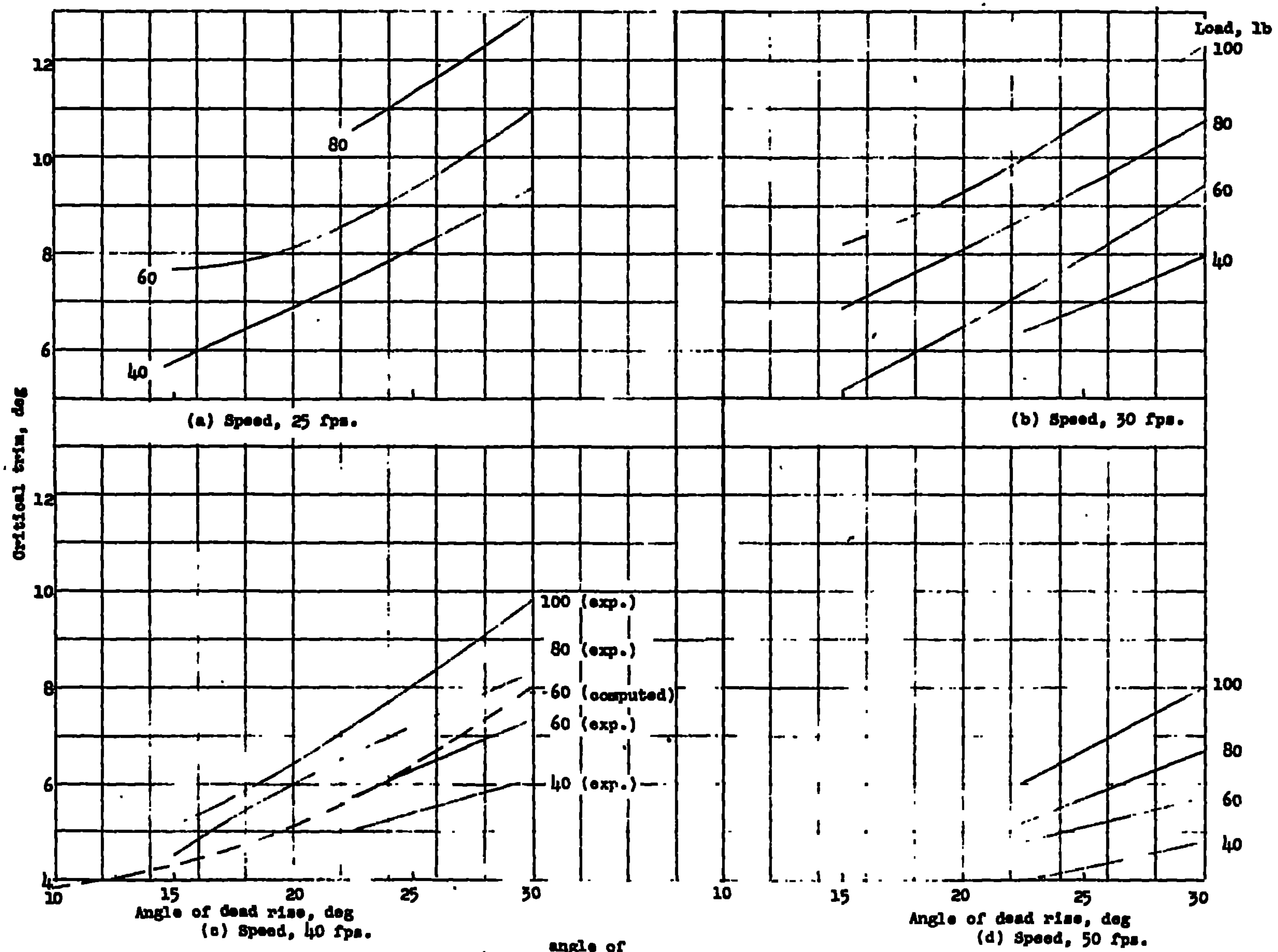

Figure 5.- Variation of critical trim with angle of dead rise for four different speeds and four different loads.

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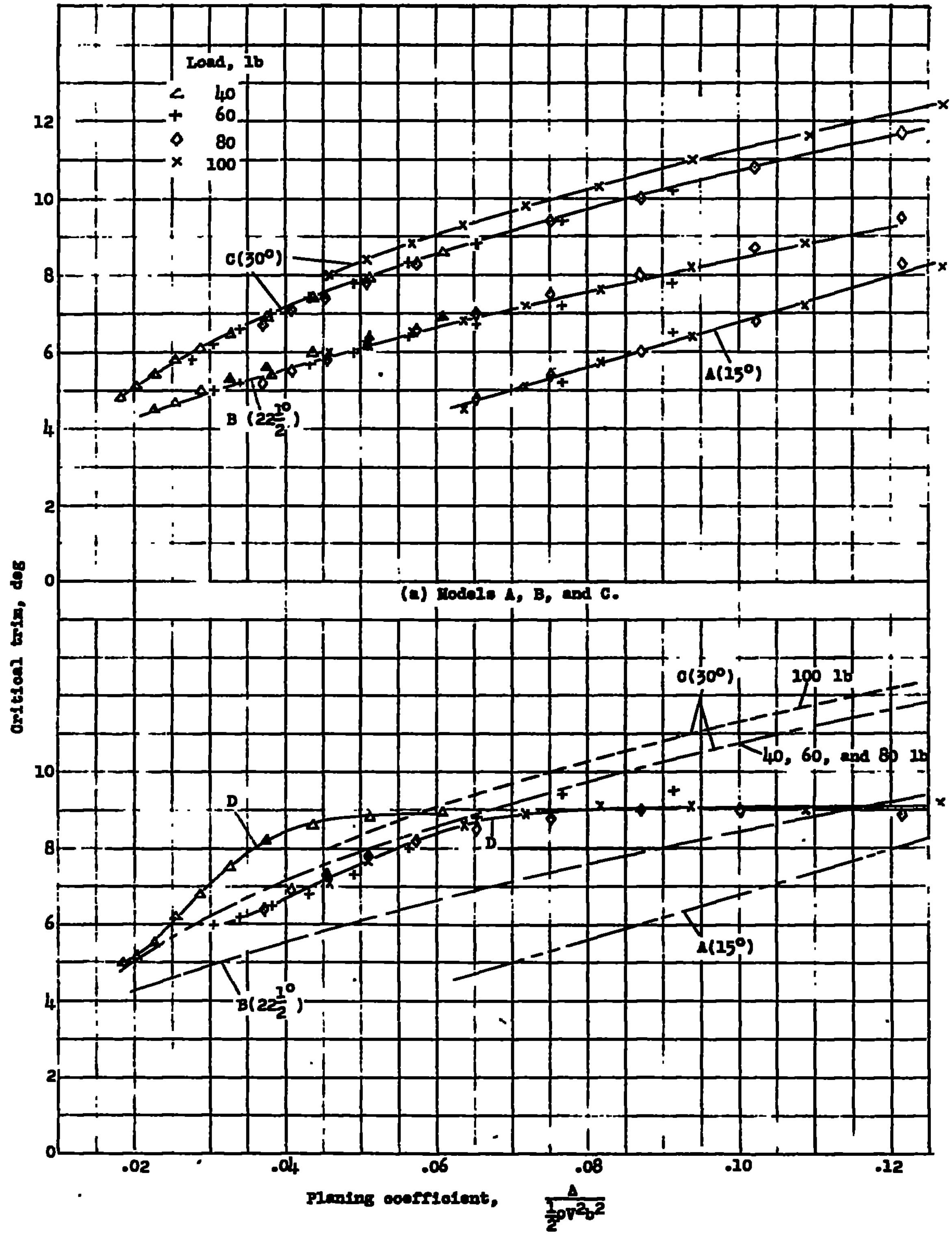
Fig. 5



(b) Model D and faired curves from figure 6(a).

Figure 6.- Variation of critical trim with planing coefficient. Plotted points are from faired curves of figure 3.